Microwave observations of planetary atmospheres

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The MAMBO team
First interplanetary space probe = first microwave radiometer

December 1962: Mariner 2 microwave radiometer ($\lambda=1.9$ cm) demonstrates that the hot microwave emission of Venus comes from the surface (limb darkening)
Planetary Science and microwave sounding

• Mariner 2…

• MIRO on Rosetta :
  – 190 GHz (1.6 mm) and 562 GHz (0.5 mm)
  – 30 cm antenna + CTS
  – CO, CH3OH, NH3 and three, oxygen-related isotopologues of water, H2 16O, H2 17O and H2 18O

• Juno on Jupiter

• More « Earth –like instrument » proposed for Mars, Titan, etc…
Juno Microwave Radiometer (Launch: August 2011):
to probe deep in the atmosphere of Jupiter

MWR probes NH$_3$, H$_2$O
An example to study Mars atmosphere
Atmospheric temperatures
(Northern winter; Mars Global Surveyor Observations
(Spectrometer TES, CO2 15 µm band inversion)
The dust cycle

- Transport
- Convection
- Turbulent mixing (PBL)
- Lifting
- Sedimentation
- Scavenging

H₂O or CO₂ ice
Global dust storms

June 26, 2001

September 4, 2001
The water cycle
An active chemistry

SIMULATION: Ozone column at the end of northern winter (movie: 4 pictures/day) (Lefevre, Lebonnois and Forget 2004)
Available observations of Mars atmosphere from Orbit

- **Profile:** Mostly temperature below 50 km
  - IR sounding
    - TES on Mars Global Surveyor, 1997-2005),
    - PFS on Mars Express (2004-present)
    - MCS on Mars Reconnaissance Orbiter (2006-present)
  - A few radio occultation and stellar occultation profiles
- **Column:** Water vapor, ice, dust aerosols
- **Ozone** observed with UV spectrometer SPICAM / Mars Express (2004)
Other key measurements obtained from Earth, in the **microwave** (thermal emission) 
(*Encrenaz, Lellouch, Moreno, Clancy, etc.*)

- Doppler shift winds
- Temperature monitoring
- H2O, HDO, CO, $^{13}$CO column
- Detection of H2O2
Microwave observations of the Martian atmosphere from orbit?

- **Lots of gas rotational lines available**
  - especially CO, used to retrieve temperature and winds: 115, 230, 345, 460, 575 GHz, etc.
  - H2O
  - Many other species: O3, H2O2, HDO, HO2, NO, etc...

- **Which frequency?**

  - **Compromise:**
    - Higher frequency: higher noise
    - Lower frequency: larger antenna required for a given beam size
    - Detailed choices driven by available gas lines (especially CO)

- **Spectrometer can be used looking Nadir, but ground-breaking science is performed by scanning the limb**
MAMBO
Mars Atmosphere Microwave Brightness Observer

λ=1 mm
ν=320–350 GHz

Heterodyne Spectroscopy

MARS
Nadir

Limb

\( z = 10 \text{ km} \)

Heterodyne spectroscopy

MARS

\( \lambda = 1 \text{ mm} \)

\( \nu = 320-350 \text{ GHz} \)

Brightness Temperature (K)

Frequency (GHz)

0 50 100 150 200 250

320 330 340 350

O3, H2O2, 13CO, H2O, HDO, CO

Limb

\( z = 10 \text{ km} \)
Science objective 1)
3D mapping of the wind from 20 to 110 km
(cross-track wind: zonal wind in polar orbit)

- Measurement of the Doppler shift on $^{13}$CO et CO (10 m/s = 10 kHz)
Doppler shift of a 13CO at 50 km (exaggerated)

Actual difference between 10 m/s shifted spectra at MAMBO resolution,
Wind retrieval accuracy

(Monte Carlo simulation)

Dash: 1s/4km

Solid: 10s/4km

(~ average of 10 measurement)
Science objective 1) 
3D mapping of the wind from 20 to 110 km

cross-track wind: zonal wind in polar orbit

- Measurement of the Doppler shift on $^{13}$CO et CO (10 m/s = 10 kHz)
- First direct wind observations from orbit
- Accuracy: ~10 m/s

=> This observations is crucial to study Mars Meteorology and climate because indirect estimation of the wind is difficult on Mars
2) 3D mapping of temperature (0-120km)

- Inversion of CO and $^{13}$CO

- Unprecedented sensitivity:
  - Insensitivity to aerosols (*affect IR below 40 km*)
  - Thermal emission a $T$
  - Well known line shape
  - Local thermal equilibrium (LTE) valid everywhere (*major problem in the IR above 70 km*)

*Simulated inversion using CO at 345.8 GHz (Bordeaux Observatory - LMD)*
*Urban et al. 2004*
Example: Northern winter dynamics

The best part is above 80 km!

LMD GCM Simulation:
Combining wind + temperature:

Winds → Data assimilation → 4D circulation of the atmosphere between 0 and 120 km!

Meteorological model

=> Comparative meteorology

=> Synergy with Netlander
3) 3D mapping of water vapor (0-60km)

- Inversion of H2O et HDO
  - Insensitivity to aerosols
  - High accuracy and sensitivity

- Water vapor + general circulation:
  => Water cycle, sources, sinks

Simulated inversion of H2O at 325.15 GHz (Obs de Bordeaux-LMD)
Water vapor profiles

Volume mixing ratio
RMS retrieval accuracy

Relative RMS accuracy (%)

Based on Simulation performed with MOLIERE, Obs de Bordeaux
4) 3D mapping of D/H ratio

- Vertical, horizontal, Seasonal variations
- Strong fractionation at condensation level
  (Bertaux and Montmessin, 2002, Fouchet and Lellouch 2001)
- Detection of ground reservoir signature?

- Determination of a reference value for Mars

**Cloud microphysics & Water cycle**

**Study of escape processes & volatile evolution**
5) 3D mapping of $\text{H}_2\text{O}_2$

- Key molecule
  (H2, O2, CO regulation)
- Recently been detected!
  (Clancy et al. 2004, Encrenaz et al. 2004)
- Surface oxidation => Exobiology

6) 3D mapping of $\text{O}_3$

- up to 70 km
- simultaneously with H2O

7) 3D mapping of $\text{CO}$

=> A complete view of Mars photochemistry
Retrieval of chemical species

CO

\[ \text{H}_2\text{O}_2 \]

\[ \text{O}_3 \]

Altitude (km)

RMS Mixing Ratio Retrieval accuracy
Mapping of the surface microwave emission and will map the variations due to:

1) subsurface ice contents (1-20 mm)
2) surface roughness (10-100 m horizontal scale)
3) CO2 ice cap characteristic
4) temperature sensing depth

Method:
- H and V polarization
- Same point observed with various viewing Angle and at different local time

Example: surface roughness Mapping at 85 GHz (Prigent et al. 1997).
12) Magnetic field
(Option ???)

- Detection of the «Zeeman» effect in the O2 emission (424.76 MHz)

- *In practice*: measurement of the difference between vertical and horizontal polarization between 30 et 60 km d’altitude

=>$\textit{Mapping of the crustal magnetic field}:
- Résolution : $\sim$50 km ? 200 km ?
- Accuracy < 1 micro-Tesla ?
Magnetic Map of Mars, altitude=200 km (Purucker et al., 2000)
MAMBO Instrument

Design: ASTRIUM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver frequency</td>
<td>323 – 347 Ghz</td>
</tr>
<tr>
<td>System Temperature DSB</td>
<td>1500 K</td>
</tr>
<tr>
<td>Maximal spectral resolution</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Antenna aperture</td>
<td>23 cm (*)</td>
</tr>
<tr>
<td>Antenna beam width at limb</td>
<td>~8 km (*)</td>
</tr>
<tr>
<td>Mass (20% margin included)</td>
<td>27.8 kg</td>
</tr>
<tr>
<td>Power (margin included)</td>
<td>62.5 W</td>
</tr>
<tr>
<td>Data rate to Earth</td>
<td>35 to 50 Mbits/day</td>
</tr>
</tbody>
</table>
MAMBO observation strategy

Total sequence: 110 s

Calibration load: 10 s

Cold sky: 5 s

Limb scanning: 35 s

Nadir (atmosphere): 3 x 5 s

Nadir (surface): 20 x 0.1 s

Cold sky: 5 s

Limb scanning: 35 s
MAMBO observation strategy

[MARS] MAMBO
Trace de l’orbite

>>> Durée représentée : 240.0 min = 0.16 sol
Trace des fauchées orthogonales

Altitude = 350.0 km
a = 3746.200 km
Inclinaison HELIOSYNCHRONE = 92.86°
Période = 116.30 min * Trs/sol = 12.72
Décalage à l’équateur = 1677.4 km (28.3°)
** Demi-fauchée : 65.0° => 1479 km [1.0 min]
MAMBO Functional Diagram

Antenna & Calibration § 3.3.1

On-board Hot Target

Cold Target

Sky

Surface

Limb

Scan Mechanism

Front-end § 3.3.2

IF Processor § 3.3.3.1

Spectrometers § 3.3.3.2

CDHS § 3.3.4

Power Supplies

Data Handling

House-keeping Controls

Power Supplies

House Keeping data

Control data

Spectrum analyser

2 CTS, 8 ACS

H2O

HDO

O3, H2O2

13CO

13CO + H2O

H2O

CO

Continuum

Continuum

2 CTS, 8 ACS

USO

IF Processor

322 - 336 GHz Receiver, L.O.

336 - 347 GHz Receiver, L.O.

Horns

Polarizer

Spacecraft Interface

Surface

Limb

On-board Hot Target
MAMBO Instrument and team

- **PI**: F. Forget (LMD)
- **Hardware development**:
  - Management: Paris Observatory, LERMA (G. Beaudin, A. Deschamps, M. Gheudin)
  - IF processor: JPL (USA) (M. Janssen, L. Riley, P. Frerking, S. Gulkis)
  - CTS Spectrometers: MPAE (Germany) (P. Hartogh)
  - ACS spectrometers: SSC/Omnisys (Sweden)
- **Science teams**
  - IPSL: LMD (M. Capderou, K. Dassas, S. Lebonnois), SA (F. Lefevre, F. Montmessin)
  - Paris Observatory: LESIA (T. Encrenaz, E. Lellouch), LERMA (C. Prigent, P. Encrenaz)
  - Bordeaux Observatory (P. Ricaud, J. Urban)
  - MPAE (Germany) (W. Markiewicz)
  - JPL, Caltech (M. Allen, M. Richadson), SSI (T. Clancy), NASA Ames (B. Haberle) (USA)…. 
Other Mars projects


• MIME (1999) proposed for Mars Express (PI : P. Hartog) 575 GHz

⇒ current concept “SWI”
The future of microwave sounding on Mars

New technologies:
• Use higher frequencies?
• Tunable receivers (frequency scanning with a synthesizer) to look for minor constituent or simplify the instrument
• Cooled instrument ???

Upcoming opportunities
• Next ESA orbiter: Mars Next in 2016. Includes a 15 kg microwave sounder in its strawman payload. Won’t happen
• Next NASA orbiter (after 2013 selected Maven): Mars Science Orbiter (2018). Includes a 30 kg microwave sounder in its strawman payload!
• Japan (2016-2018)?
ANOTHER EXAMPLE: A sounder for Titan aboard the TANDEM mission.
Titan:

Photochemistry:

$N_2 \rightarrow C_2H_2, C_4H_2 \rightarrow \text{Polymers} \rightarrow \text{precursors, aerosols}$

$\text{CH}_4 \rightarrow \text{HCN, HC}_3\text{N}$

growth with mass incorporation from gas phase

negligible mass gain

Microphysics:

Main haze layer

Aerosol haze

Methane clouds

Methane/ethane rain?

Temperature (K)

Pressure (bar)
The case for a submillimeter sounder on the TSSM Titan Orbiter

E. Lellouch, S. Vinatier, P. Hartogh, G. Beaudin, R. Moreno, …, et al.

Presented at TSSM meeting Meudon, 19 March 2008
A model of Titan’s (nadir) spectrum as seen by a heterodyne spectrometer

All calculations by S. Vinatier
Titan’s expected spectrum at 1.0-1.3 THz

HCN CO CH4
**Thermal sounding**

- From CH$_4$ (uniform): up to $\sim 500$ km
- From CO (almost certainly uniform); no homopause uncertainty problem: up to $\sim 800$ km
- From HCN (not uniform vertically nor spatially, but feasible through multiple lines incl. isotopes, cf. CO on Venus): up to $\sim 1200$ km

- Advantage: *LTE is not a major issue like in IR*
- Vertical resolution $\sim 8$ km (width of contribution functions)
- Expected precision $\Delta T \sim 1$ K in 1 min observation
Science goal # 1: Temperature sounding

• **Approach:** use HCN, CO and CH4 to retrieve $T(z)$
  • CO and CH4 probe atmosphere up to $\sim$800 and $\sim$400 km respectively and are horizontally/vertically uniform in range of interest.
  • HCN is not uniform but optically thick up to 1150 km; combination with INMS-like instrument possible higher up.
• **Advantages:**
  • good sampling of 40-1200 km range
  • vertical resolution $\sim$ 8 km (width of contribution functions)
  • expected precision $\Delta T \sim 1$ K in 1 min observation
  • **rotational LTE** valid to very high altitudes (typically $\sim$ 10-11 bar $\sim$1250 km)
**Science goal #2: Direct wind measurements**

- **Approach:** Direct absolute wind measurements from Doppler shift on any optically thin line.

**Advantages:**
- No assumption on thermal field equation validity or boundary condition
- Precision 3-4 m/s for $\Delta T \sim 100$ K contrast line in 1-min
- Possibility to measure zonal winds (off-track from polar orbit) and meridional wind (in-track)
**Science goal #3: Chemistry and coupling with dynamics**

- **Goals:**
  1) determine vertical/horizontal distribution of several minor species with various chemical lifetimes (HCN, HC3N, CH3CN, CH3CCH, H2O) and relate it to the global wind field (and possibly to source of oxygen).
  2) Search for species yet undetected in stratosphere/mesosphere (HC5N, C2H3CN, NH3, CH2NH) and compare chemical complexity to thermosphere as seen by INMS.
  3) Determine yet un-established isotope ratios (16O/18O in CO, D/H in HCN and H2O).
Preliminary instrument characteristics

- **D= 15 cm-antenna with articulation system, allowing limb and nadir sounding**
  - In track-views needed for meridional winds and to perform limb sounding over poles
  - Off-track views needed for zonal winds
- **Two receivers sharing common and tunable LO system**
  - 1 “high-frequency” band (e.g. 540-640 GHz; or 1080-1280 GHz)
  - 1 “low-frequency” band (e.g. 300-360 GHz band)
- **Typical spatial/vertical resolution ~ 4 mrad @ 600 GHz (∝ 8 km @ 2000 km)**
- **Instantaneous bandwidth: 1 GHz @ 300 kHz resolution**
- **Uncooled Schottky receivers: Tsys (DSB) ~6000 K at 1 THz, ~4000 K at 600 GHz, 2500 K at 350 GHz**
- **Typical performances: ΔT (1 σ) in 1 MHz = 0.6-1.5 K in 1 min; 0.08 K - 0.2 K in 1 hour**
Conclusions

- Limb Sub-mm atmospheric sounding will be used in future planetary missions
- Key objectives: Doppler winds, temperature, trace species
- Need for wide band / tunable receivers to monitor several lines with a light instrument
- **Key compromise**: Noise/antenna size/gas lines target/vertical resolution
  - need to define acquisition time when designing/comparing concepts.